NATIONAL CENTER FOR EARTHQUAKE
ENGINEERING RESEARCH
State University of New York at Buffalo

WORKSHOP ON SERVICEABILITY ANALYSIS OF WATER DELIVERY SYSTEMS

December 1-2, 1988

Edited by

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Technical Report NCEER-89-0023

March 6, 1989

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SERVICEABILITY ANALYSIS OF WATER DELIVERY SYSTEMS

held at
Cornell University
Ithaca, New York
on
December 1-2, 1988

Technical Report NCEER-89-0023

Edited By: Mircea Grigoriu[1]
March 6, 1989

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PREFACE

The National Center for Earthquake Engineering Research (NCEER) is devoted to the expansion and dissemination of knowledge about earthquakes, the improvement of earthquake-resistant design, and the implementation of seismic hazard mitigation procedures to minimize loss of lives and property. The emphasis is on structures and lifelines that are found in zones of moderate to high seismicity throughout the United States.

NCEER's research is being carried out in an integrated and coordinated manner following a structured program. The current research program comprises four main areas:

- Existing and New Structures
- Secondary and Protective Systems
- Lifeline Systems
- Disaster Research and Planning

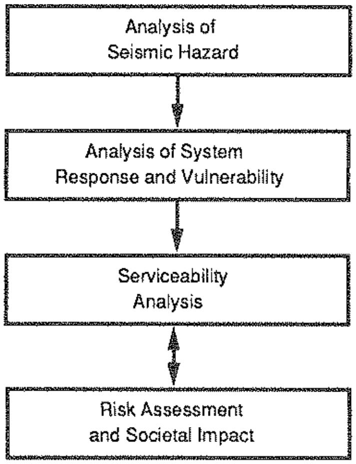
This technical report pertains to Program 3, Lifeline Systems, and more specifically to water delivery systems.

The safe and serviceable operation of lifeline systems such as gas, electricity, oil, water, communication and transportation networks, immediately after a severe earthquake, is of crucial importance to the welfare of the general public, and to the mitigation of seismic hazards upon society at large. The long-term goals of the lifeline study are to evaluate the seismic performance of lifeline systems in general, and to recommend measures for mitigating the societal risk arising from their failures.

From this point of view, Center researchers are concentrating on the study of specific existing lifeline systems, such as water delivery and crude oil transmission systems. The water delivery system study consists of two parts. The first studies the seismic performance of water delivery systems on the west coast, while the second addresses itself to the seismic performance of the water delivery system in Memphis, Tennessee. For both systems, post-earthquake fire fighting capabilities will be considered as a measure of seismic performance.

The components of the water delivery system study are shown in the accompanying figure.

Program Elements:



Tasks:

Wave Propagation, Fault Crossing
Liquefaction and Large Deformation
Above- and Under-ground Structure Interaction
Spatial Variability of Ground Motion

Soil-Structure Interaction, Pipe Response Analysis
Statistics of Repair/Damage
Post-Earthquake Data Gathering Procedure
Leakage Tests, Centrifuge Tests for Pipes

Post-Earthquake Firefighting Capability
System Reliability
Computer Code Development and Upgrading
Verification of Analytical Results

Mathematical Modeling
Socio-Economic Impact

An NCEER-sponsored two day workshop was held at Cornell University on December 1-2, 1988 on serviceability analysis of water delivery systems. This report summarizes the technical presentations given on the first day, and the position papers written by two discussion groups on the second day of the workshop. The position papers deal with methods for serviceability analysis, design, operation and rehabilitation of water delivery systems.

ABSTRACT

A two day workshop was held at Cornell on December 1-2, 1988 on serviceability analysis of water delivery systems. The major objectives of the workshop were (i) evaluation of methods for serviceability analysis of water delivery systems and (ii) development of rational strategies for design, operation and rehabilitation of these systems. Technical presentations were given by participants on the first day of the workshop. Participants also had the opportunity to use the Cornell interactive computer graphics for serviceability analysis of water delivery systems. The second day was spent on panel discussions and preparation of position papers on methods for serviceability analysis, design, operation, and rehabilitation of water delivery systems. These position papers were reviewed by all participants and are included in the report. The report also contains abstracts of all technical presentations.

ACKNOWLEDGEMENTS

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The workshop and this report could not have been possible without the support of Professor M. Shinozuka, Professor T. D. O'Rourke, Dr. M. Khater, and Dr. C. Scawthorn. Their efforts as well as the enthusiastic cooperation of all participants are gratefully acknowledged. Staff support has been provided by Pam Welzel.

Any opinions expressed herein are those of the editors and authors only and do not reflect the views of the sponsor.

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SECTION 1
INTRODUCTION

Twenty-one experts on emergency response and water delivery systems from industry and academia participated in a two-day workshop held at Cornell University. The group consisted of managers of water distribution systems, fire chiefs and fire marshalls, engineering consultants, and engineering professors. Representatives of the water supply management and fire departments of Memphis, Los Angeles, and San Francisco were present. The workshop was organized by Dr. Mircea Grigoriu, a Professor of Structural Engineering at Cornell University.

Presentations during the workshop focused on two topics:

(1) Methods for serviceability analysis of water delivery systems, and
(2) Methods for rational design, operation, and rehabilitation of these systems.

Two working groups were formed to develop position papers on the workshop topics. These papers were reviewed by all participants. The following sections include abstracts of technical presentations and a summary of the position papers.

Appendix A gives the program and schedule of the workshop. The first day involved technical presentations and discussions by participants and demonstrations of the Cornell interactive computer graphics analysis program, GISALLE, for serviceability analysis of water supply systems. The second day consisted of presentations of position papers on the main topics of the workshop.

Appendix B presents a list of the participants who attended the workshop. All participants are actively involved in the planning and engineering of water delivery systems.

SECTION 2
ABSTRACTS OF TECHNICAL PRESENTATIONS

2.1 Serviceability of Water Delivery Systems (Frank T. Blackburn) Earthquakes and the fires that follow have always been of serious concern to the City of San Francisco. Following the 1906 earthquake, 52 fires broke out, raged for 3 days and destroyed 28,000 buildings. Following that disaster, the people of the City voted for a bond issue that installed a special pipeline system, designed to resist the forces from an earthquake, this is called the Auxiliary Water Supply System, or the High Pressure System. It is capable of providing 330 psi at hydrants at lower elevations with 6,000 gpm flow. This system allows the fire department to take water from such hydrants without additional pumping, the high pressure hydrant in effect becomes a pumper. In addition, 151 underground cisterns of 75,000 gallon capacity were built as well. This system of cisterns provides an additional emergency water supply if all other systems failed. As San Francisco expanded since 1912, when the original systems were built, emergency water supply in the outlying residential districts was deficient. In November of 1986, a new proposal was presented to the voters, a 21 mile expansion of the high pressure system, construction of 95 additional cisterns, installation of suction connections to San Francisco Bay and city lakes for pumpers to take draft and an additional 20,000 gpm pump station at Lake Merced for the high pressure system. Finally a new system of portable hydrants and large diameter hose into a portable water system to deliver water from sources of supply to the fire scene was developed. These systems when all completed will give S.F. a degree of readiness. The voters passed this proposition by a 89.5% vote, which was a record for a bond issue in San Francisco. The bond issue was for $46.2 million. Work has begun on the extensions and new cisterns, and it is significant that this is the largest expansion of the emergency water supply system since it was constructed in 1912. It demonstrates the concern of the people when an emergency system is properly presented to the public. A previous research report by the Cornell University Engineering Department was instrumental in securing this bond proposal, as the report detailed the problems of water supply and the probability of fire outbreak following another major earthquake in San Francisco.

2.2 Firefighting After the Earthquake - A Los Angeles Scenario

(Frank W. Borden)

The City of Los Angeles covers 466 square miles and is the second largest city in the United States with a population of over 3.5 million people. The potential for major life loss, injury and property damage as a result of an earthquake of a magnitude of 6 or greater is significant. The 1933 Long Beach Earthquake, the 1971 San Fernando Earthquake, and the 1987 Whittier Earthquake provided valuable experience and lessons for our City, government and Fire Department in understanding the earthquake threat and developing plans to mitigate the effects of a damaging earthquake. Given our national topography, climate, and growing build up of population, structures and industry, the threat of fire and hazardous materials releases following an earthquake pose a major problem for our Fire Department and the community. The scenarios developed for an 8.3 magnitude earthquake on the southern San Andreas Fault and a 7.0 magnitude earthquake on the Newport/Inglewood Fault suggest that our water systems will suffer major damage to transmission, distribution, and supply networks. In addition, we anticipate a large conflagration risk and threat of fire outbreaks on a widespread basis.

Our Department, after the San Fernando Earthquake, developed an Emergency Earthquake Operational Plan that changes the normal response of our fire suppression and medical delivery systems into an earthquake mode of operation. Because of anticipated disruptions to our firefighting water supply systems, we developed several alternative methods of water supply such as portable tanks, relay and drafting pumping operations, as an example, and have identified various sources of water supplies such as swimming pools and water tanks. We have also developed various fire suppression strategies to assist us in coping with this fire problem. Our Department's recently formed Disaster Preparedness Division, has undertaken a major effort to train Community and Business Emergency Response Teams who could, in the event of an outbreak of fire, initiate immediate suppression operations. We have also determined that it may be necessary in our strategic considerations to change from the offensive firefighting strategy to a defensive firefighting strategy, using natural or man-made fire breaks as a line of defense against spreading fire fronts.

Our City is very concerned about the earthquake threat and all aspects of the potential damage and disruption it may cause and for many years have been developing plans to mitigate the effects such as developing stringent building codes, zoning regulations, response plans, communication systems, and a very effective City Emergency Operations Organization. Preplanning, risk assessment and development of systems such as the serviceability of water delivery will be a key to our survival.

2.3 Suggestions for Mitigation of Earthquake Damage to Intakes and Pump Stations (Holly A. Cornell)

Intakes and pumping facilities are vital links in maintaining serviceability of water delivery systems. Seldom are redundant facilities available. Intakes in particular are usually singular facilities, and when the intake and pump station are combined in the same facility, vulnerability and risk are increased.

Review of the performance of these facilities during earthquakes leads to the conclusion that the inability to function after an earthquake is generally not the result of improper design or construction per se, but the result of a lack of attention to detail, failure to apply common sense, or secondary causes. Exact analysis is not essential in designing intakes and pump stations, but imaginative consideration of possible failure or damage modes and adoption of measures to mitigate such damage is critical.

Because these facilities or their components are often massive structures, the integrity of the foundation is critical. Water intake structures, typically tower type structures located in water impoundments, may be founded on unstable submerged strata vulnerable to displacement.

The greatest damage to pumps and equipment during earthquakes has historically occurred when earthquake-induced forces have not been taken into account during design and installation.

In designing for earthquake, the soils and foundation investigation is essential to providing seismically stable foundations protected against liquefaction, settling, etc. Often it is necessary to support structures, particularly intakes on lake or river bottoms, on piles or otherwise stabilize the underlying soil.

The structural design of concrete intake and pump station structures should consider the provisions of "ACI Concrete Sanitary Engineering Structures" (ACI-350). This requires design on the basis of elastic distribution of stress. Basins containing liquid must be analyzed for the sloshing action caused by an earthquake.
Flexible connections must be provided between the facility and its inlet-outlet piping. It is essential to provide flexibility and ductility in all piping through choice of material or in the pipe joints.

All equipment should be positively anchored and seismically qualified. Secondary systems on which major equipment relies are as critical as the primary equipment itself and must have the same level of seismic resistance. Electric power supply, cooling water, controls, fuel, lubrication (seal water), exhaust, starting systems, etc., may seem minor items, but failures in these systems have been one of the most vexing problems in earthquakes. Power supply or standby must be assured.

2.4 **Review and Comments of "Priorities For Rational Design In Rehabilitation of Water Delivery Systems"** (H. D. Crossnine)

1. Communities must first accept the idea that they are in a seismic zone before they will commit to this endeavor. For example, the City of Memphis has been debating for many years the need for seismic considerations in building design. With all the pressing, immediate problems cities are faced with daily, one that occurs every 100 years receives less attention. Were it not for a seismic study committee that reviewed the preponderance of evidence indicating the need for seismic design in our area, there is a possibility it would not be up for adoption in the new building code. I would suggest that the cost benefit analysis takes this in consideration by providing data to a community that puts them in a high risk area.

2. The Master Plan for Development must include items from priorities 1, 3, 4, 5 and 6, because Cost Benefits, Improved Maintenance, Emergency Planning, Valve Arrangement and Definition of Ground Failure are to be considered in any master plan.

3. In gathering maintenance records, one must take into consideration that a large percentage of water mains are not installed and maintained by the public utilities but by private contractor on private property, examples are apartment complexes and large warehouse developments. It has been our experience in the City of Memphis that plastic pipe is used on most of these projects. Maintenance of these systems are the responsibility of the private owners and records of the public utility will not reflect this.

4. Development of any emergency plan should include all segments of the community in its planning stage to utilize their talents and resources. There should be a yearly exercise to demonstrate the strength and weakness of the plan. The built in capability of each city or county department should be considered first. It has been our experience that cooperation with private industry is successful when they are part of the emergency planning team. Examples: Fire sprinkler companies can be utilized in time of emergency to assist in the installation of valves for the emergency supply of water to a given location. Irrigation companies can be called on to utilize the portable piping to route water. Fuel for emergency pumps, generators, etc., can be obtained from a local refinery or fuel storage facility. One must keep in mind that in most communities the prime portable mover of water is the fire department with most pumpers designed to deliver 1500 gpm. Fire departments will always have considerable amounts of extra fire hose and proper valving available in time of emergency.

5. Valving arrangement has to receive special attention. The location and operation of these valves are critical in localizing water main failures and diverting water flow to areas where needed. The computer assisted program will assist in the location of the valves but

key valves on the system should be remotely controlled and operated. Some identification marker should be placed on all sectional valves to aid in quickly locating these valves. Fire experience indicates that delay in fire suppression leads to fire development that overtaxes the local fire department and can result in a conflagration.

6. Identifying ground failure hazards will be useful especially in cities that have soil conditions that differ from the ones where recent earthquake studies have been done. For example, the alluvial soil in Memphis, with a depth of 2000 ft, should react differently than the soil on the west coast. The results could mean substantial more damage to buried pipelines. Identifying these inherent problems would be another means of focusing local attention to this matter.

2.5 Serviceability Analysis of Water Delivery Systems (Mircea Grigoriu)
Serviceability analysis of water delivery systems involves network representations, models of component failure, and performance measures. Development of a computerized representation of a network may be a lengthy process depending on the size of the network and the degree of refinement in modeling. Nevertheless, it has to be performed only once for a particular network. Component failure should account for effects of likely hazard scenarios and normal operation. System serviceability can be estimated from results of repeated hydraulic analyses for simulated damage states and demands. It can be measured, e.g., by the ratio of available flow in a damage state consistent with a specified hazard scenario to available flow in the undamaged state.

A general interactive-graphical preprocessing and postprocessing code, GISALLE, has been developed at Cornell for serviceability analysis of water delivery systems. The program can be applied to the analysis of large networks. It is based on a new algorithm for hydraulic analysis and provides several serviceability measures. The Auxiliary Water Supply System in San Francisco is one of the networks stored in GISALLE's library and has been studied extensively by the Cornell research team. Figure 2-1 shows a representation of this system used in GISALLE.

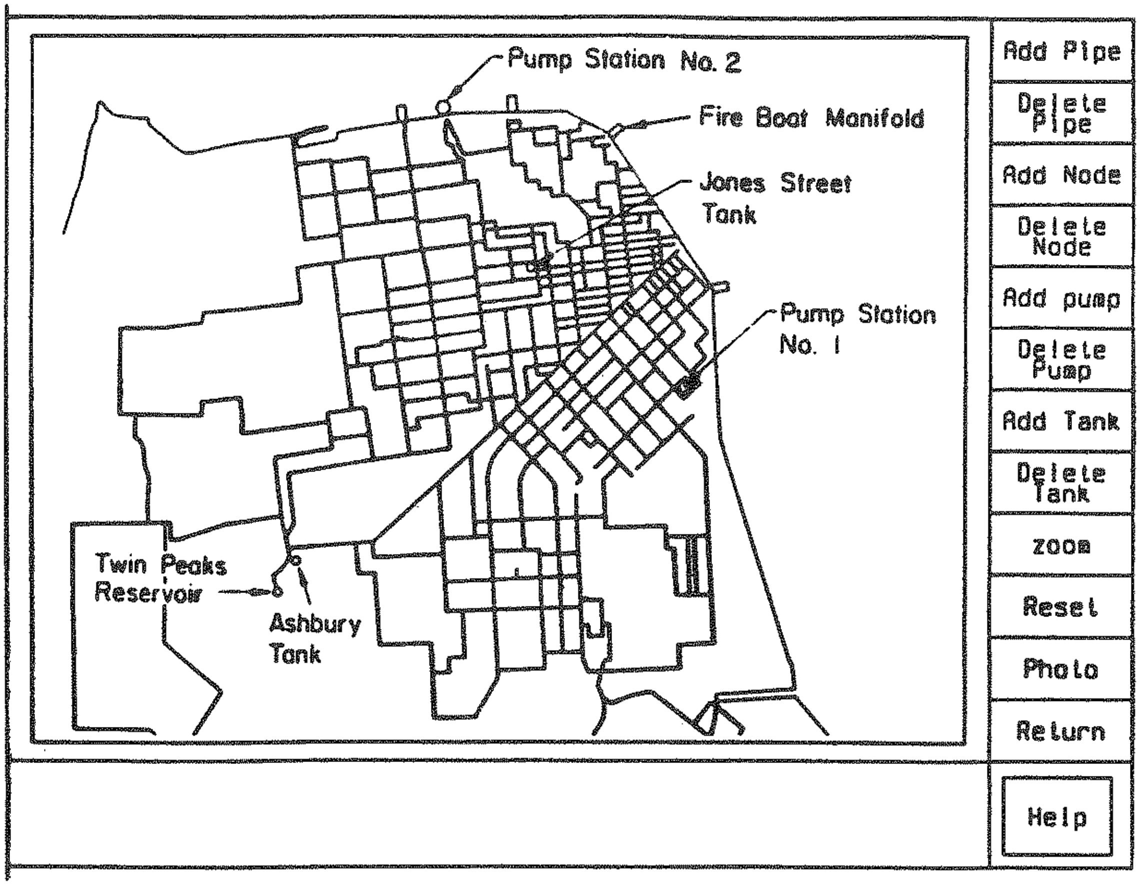

Figure 2-1. Computer Model of AWSS in San Francisco

2.6 Correlation Between Corrosion and Earthquake Damage to Pipelines; Accelerated Aging (Jeremy Isenberg)

Post-earthquake reconnaissance of at least four U.S. earthquakes strongly suggests that leaks in iron and steel pipe due to ground shaking from wave propagation is greater where corrosion has locally thinned the walls. Data obtained following the 1965 Puget Sound, 1969 Santa Rosa, 1971 San Fernando and 1983 Coalinga earthquakes indicate at least 50% of the leaks occurred at points already weakened by corrosion. This observation, if confirmed, suggests that regions where pipeline repairs exceed the average for the system as a whole may also be more likely to be damaged by ground shaking from seismic sources.

Post earthquake studies also indicate that pipeline systems can retain a memory of having been subjected to earthquake shaking. Thus, not all pipeline damage results in leaks that appear within hours or days following the earthquake. Instead, the leak rate has been observed in several cases (San Fernando, Coalinga) to exceed the pre-earthquake rate by a substantial margin; for example, at Coalinga, the post earthquake rate was for several years 50% greater than the pre-earthquake rate. The effects of this delayed damage, which has also been described as "accelerated aging", on eligibility for disaster relief funding needs to be examined.

Pipeline Experiment at Parkfield, California. Investigators from Weidlinger Associates, with the assistance of consultants from Cornell University, have installed welded steel and segmented ductile iron pipes across a fault near Parkfield, California. The U.S. Geological Survey predicts with high probability that an earthquake of Magnitude 6.0 will occur on this segment of the San Andreas Fault within the next 5 years. Responses of the pipeline segments and of the nearby ground will be measured. Following the occurrence of the earthquake, researchers will analyze the resulting data to learn more about this type of pipeline performance in fault-crossing situations. In addition, the results are intended as one step in a process leading to a code of practice for designing pipelines used in seismic areas.

The two, 200-foot welded steel pipe segments are instrumented with 36 strain gages and two temperature sensors; the ductile iron pipes are instrumented with 12 extensometers. A line of survey monuments has been established across the anticipated zone of surface rupture in order to measure lateral offset accompanying the earthquake. Three strong motion seismometers, contributed by the Disaster Prevention Research Institute of the University of Kyoto, have been installed adjacent to the pipeline array. These have time in common with the active strain and extensometer measurements in order to correlate these quantities with ground strain. Pipe segments were buried by October, 1987 and data logging began in January, 1988.

Microearthquakes, fault creep, outgassing from wells and other premonitory signs on which seismic alert levels are based are monitored continuously by USGS. At present, the seismic alert level in the Parkfield area is low. However, the USGS continues to predict that a moderate earthquake will occur in this segment of the San Andreas Fault within the next few years.

2.7 Mitigation of Seismic Effects of Water Systems (Michael J. O'Rourke)

Historically, earthquakes have caused damage to water systems. In this paper, water system facilities at risk due to seismic activity are identified.

Methods to mitigate the effects of an earthquake on an existing water system are considered. The potential damage mechanisms, seismic shaking, permanent ground deformation, etc., are identified. Two forms of mitigation are then discussed. The first is physical damage mitigation wherein various system components are strengthened or retrofitted with the objective of eliminating seismic damage. Physical damage mitigation techniques for buildings, dams, treatment plants, and some buried piping are briefly described.

Impact mitigation is proposed for elements which are not amenable to physical damage mitigation. Examples of such elements are buried segmented pipelines subjected to seismic wave propagation or continuous pipelines subject to lateral spreading. Effective impact mitigation requires preparation of a disaster plan before the earthquake. The plan should address the problems of increasing serviceability of the existing system, water supply immediately after the earthquake, and rapid repair.

A disaster plan requires information on the expected condition of the existing system immediately after the earthquake. Examples of some of the available information in this regard are provided.

Finally, St. Louis, Missouri is presented as a case study. Estimates of the effects of a large earthquake in the New Madrid seismic zone are summarized.

2.8 Computer Assisted Systems Engineering for Water Supply
(Thomas D. O'Rourke)

Given the rapid development in computer technology, numerical simulation promises to be a major tool for utility improvement. With interactive graphics, utility personnel can perform complex hydraulic analyses, change pipeline network configurations, and explore maintenance and operational strategies with ease. Moreover, graphical displays assist in communicating information, and can be particularly effective in communicating complex processes to operational personnel as well as supervisors, boards of directors, and the public.

Pipeline systems involve many different components, of varying age, constructed according to different standards of manufacture and field installation, and subject to a wide variety of loading environments. Because pipeline systems cover large areas, earthquake effects will vary in severity as a function of distance from the epicenter, site amplification characteristics, and the potential for ground failure. Probabilistic methods for assessing risk and system response provide a means of accounting for uncertainties inherent in pipeline network operation and earthquake loading.

At Cornell University a methodology has been developed for estimating the seismic serviceability of water supply systems. The methodology can account for uncertainties in earthquake, mechanical properties of soil and pipelines, and water demand. An interactive-graphical preprocessing and postprocessing computer code, GISALLE, has been developed based on this method. The code is applied to the serviceability analysis of the Auxiliary Water Supply System in San Francisco.

San Francisco is well suited for such a study. After the 1906 earthquake, ruptured water pipelines and subsequent fires resulted in the largest single earthquake-related loss in United States history. More than four square miles of the city burned, destroying 490 city blocks and causing partial destruction of thirty-two additional blocks. The geotechnical hazards in San Francisco include soils susceptible to liquefaction, landslides, and settlement. Over 80 percent of the water distribution network is composed of cast iron pipelines, and therefore is typical of many midwestern and eastern cities where earthquake damage should be an important aspect of planning for disaster relief, although it is still relatively unstudied.

San Francisco is served by the Municipal Water Supply System and by the Auxiliary Water Supply System, which was established to protect those areas most severely damaged by the 1906 earthquake. The auxiliary system comprises about 200 km of pipeline, two pump stations, and five manifolds that serve one fire boat. This system is the backbone of fire protection for San Francisco.

The interactive user friendly computer model, GISALLE, has been checked successfully against special fire flow tests run by the fire department. This computer model is built around a hydraulic-pipeline-network program that has been modified so as to allow the simulation of possible post-earthquake damage states. A new code has been developed for GISALLE to model accurately the hydraulic performance of damaged systems with many pipeline breaks. Pipe breakage caused by traveling ground waves is assumed to occur as a Poisson process, and is calibrated according to pipe damage statistics from previous earthquakes. For permanent ground movements, the likely locations of pipeline breaks are established by means of subsurface surveys and studies of geotechnical site characteristics. The computer model assesses the water flow and pressure at critical hydrants and compares these with estimated demands in the event of fire. These estimates are generated by a probability-based program, developed by Dames & Moore, and EQE, Inc., for fire initiation and spreading. The hydraulic-network model can simulate pump stations and fire boat manifolds so that a full range of emergency response options can be explored.

Serviceability indices are used to develop fragility curves based on regression analysis according to the following procedure. First, several earthquake intensities I and corresponding mean break rates F(I) are selected. Then, damage states are generated for each value of I, and available flows $q_<$ (I) are obtained by hydraulic analyses. Regression analyses are then performed to estimate system serviceability as a function of earthquake intensity.

The workshop demonstration of GISALLE may be regarded as proof of concept for an approach to pipeline networks, which we refer to as Computer Assisted Systems Engineering (CASE). This approach involves two levels of logic affecting water supply systems, which are distinctly different.

There is a structural logic inherent in the way the pipeline network is modeled; this logic requires multi-disciplinary input from engineers to account for the hydraulic, mechanical, and geotechnical aspects of the system. There also is an operational logic, which depends on the ways utility engineers work with the system. This logic requires input about personnel allocation, budgets, accessibility, and field experience.

By providing the structural logic as an interactive computer graphics system, CASE allows the utility engineers to work within their operational constraints as they explore various scenarios in an environment of simulated system response. A computer program, like GISALLE, can show the interrelationship among system components, assess rapidly the effects of modifications in the system, and estimate losses for an earthquake. In addition,a computer graphics approach provides a computerized data base and can aid substantially during normal operations in the assessment of repair records and the forecast of future needs. These services are of critical importance for infrastructure renewal.

The combination of computer simulation and pipeline instrumentation could help to create a "smart" system, in which instrument feedback of flow and pressure loss is checked against system models to provide the most likely scenario for dispatching engines and repair crews immediately after an earthquake. Computer simulations can also be used with remotely controlled valves to isolate breaks and rapidly reassess the hydraulic capacity of the remaining network as a basis for decisions about emergency operation.

2.9 Serviceability Analysis of Water Delivery Systems (M. Shinozuka)

The presentation outlined an analysis method of estimating the probability of a water delivery system to remain serviceable immediately after a severe earthquake. A water transmission system adapted from the Los Angeles City system was employed as an example to demonstrate the application of the analysis method.

The method takes into account the existence of major surrounding and penetrating faults, topological and structural characteristics, soil and ground conditions, and the location and magnitude of future earthquakes. In addition, it is postulated that the water transmission system is serviceable when its fire-fighting capabilities (measured in terms of water pressure and flow rate at specified nodes) remain intact immediately following an earthquake. Based on the probability of pipe failure, Monte Carlo techniques are used to generate a sample of simulated states of damage for the water transmission network. The Newton-Raphson method is then utilized to perform a flow analysis on each of these damaged networks and, at the same time, to determine whether or not it still remains serviceable. The probability of system serviceability is estimated as the rate of the number of damaged states of the network thus simulated that are found to be serviceable to the sample size used for the simulation. An advantage of hierarchical features of lifeline systems are also utilized to perform functional reliability analysis of large-scale network systems.

The analysis consists, first, of assessing the probability of pipe failure, the second, of evaluating system serviceability, and the third of introducing the reliability analysis technique by viewing the water delivery system as a hierarchical network system. In each part, the essential theoretical background was discussed.

2.10 **On General Advances and Needs in Seismic Risk Analysis of Water Systems** (Craig E. Taylor)

The presentation was intended to discuss general advances and needs in lifeline seismic risk analysis. These advances and needs were identified as a consequence of the application of risk analysis techniques to many water transmission systems as part of USGS, NSF, ASCE TCLEE, and client projects. The discussion of advances and needs were organized into four main topic areas that represent phases of seismic risk methods: inventory procedures, hazard identification, component vulnerability analysis, and systems analysis (including analysis of such secondary systematic consequences as fires and unemployment). The discussion was intended to lead into a discussion of response to needs and general advances in the National Earthquake Engineering Center program. Inventory procedures have to date been highly time-consuming. The use of superior geographic data base systems, especially those with analytic capabilities, has the promise to meet various seismic risk project objectives more effectively than has been done in the past. Reduction in inventory time, maintenance of a permanent database that can be updated, the ability to combine data sets developed in terms of adverse geographic reference systems, use of the database developed in analytical routines, and effective display of project outcomes are all key objectives in moderate to large-sized projects.

Two key areas continue to require research in hazard identification: (1) the efficient modeling of representative earthquake scenarios and (2) the estimation of ground-failure probabilities. The first area requires continued modeling efforts, and may be considered as part of a larger problem of modeling the uncertainty of numerous parameters in seismic risk analysis and these comparative influence on study outcomes. Biases resulting from selection of magnitude and rupture center (and/or hypocenter) have been shown to be significant in many past projects. Extension of modeling to random areal source zones has begun in a current USGS-sponsored project. The second area requires further research in order to reduce uncertainties that result from diverse approaches to modeling ground-failure probabilities.

Seismic vulnerability analysis continue to improve -- especially with respect to pipeline modeling. This is partly because many practitioners, including Eguchi, Wang, Isenberg, M. O'Rourke, D. Ford, T. O'Rourke and C. Trautmann, have paid considerable attention to earthquake field data. Currently, there is clear need to have more organized post-disaster reconnaissance efforts that inventory the existing universe of affected facilities as well as assess those that are damaged.

Systems analysis continues to be computationally intensive. So far, it is not clear how to eliminate Monte Carlo analysis from more complete systems analyses that incorporate flow models. This implies as well that results of an adequate number of Monte Carlo trials have the potential to be very confusing to end-users. A crude distribution between "breaks" and "leaks" was indicated as a possible vehicle to proceed directly from estimation of damage states to application of flow analysis. This distinction, however, does not at face value eliminate the need for Monte Carlo analysis.

2.11 **Earthquake Preparedness Program at The Metropolitan Water District of Southern California** (Charles F. Voyles)

Metropolitan embarked on a formal Earthquake Preparedness Program in early 1974. There are three principle aspects of the problem which were identified: 1) to review existing facilities in the system and make modifications to improve their resistance to earthquakes; 2) design new units and modify existing units using the latest applicable earthquake design criteria and techniques; 3) develop an emergency response capability to respond to earthquakes when they do occur.

The following factors were considered in performing an evaluation and developing priorities for the earthquake preparedness activity:

1. The relative seismic risk at each facility based on the maximum probable earthquake potential for ground shaking, liquefaction, landslide, etc.,
2. The function provided at each facility,
3. The vulnerability to earthquake damage of the specific pieces of equipment and structures at each site,
4. Evaluation of the risk versus the cost for reducing that risk.

The initial program dealt with primarily nonstructural equipment at critical facilities where the emphasis was on hazards or conditions that could be corrected or improved as part of routine maintenance by regularity assigned field personnel. More than one hundred structures and major facilities were reviewed for earthquake vulnerability. These inspections have been accomplished approximately every three years with the necessary work to provide the increased reliability being accomplished within six months of each periodic review.

Approximately 12 million dollars have been spent over the past 15 years in the long-range program involving new design and structural modifications of existing facilities.

A formal Emergency Response Program was developed and implemented in 1976. There have been several opportunities to exercise the program in responding to actual earthquakes. Each time an evaluation is made of our capability to respond and modifications are included in a revised program.

The principle reason for the success of this activity at Metropolitan is due to the broad support of the Board of Directors as well as our top management throughout the years. We have all adopted a frame of mind that accepts the fact that a damaging earthquake is coming some time soon rather then at some distance uncertain time in the future. We are certain that we will suffer less damage and be able to respond and cope with the big earthquake much better as the result of all the effort that has been put into this emergency preparedness program.

2.12 Some Aspects of Seismic Analysis/Design and Research Needs of Buried Water Pipelines (Leon R. L. Wang)

Recent studies have shown that lifeline systems, which include transportation lines, water and sewer pipelines, oil and gas pipelines, electric power transmission lines, long span bridges, etc., have been damaged heavily by recent earthquakes including the recent 19 September 1985 Mexico Earthquake and October 1, 1987 Whittier California Earthquake.

In general, there are three causes of seismic hazards to buried pipelines namely: a) soil straining induced by seismic ground waves, b) fault movement/ground rupture and c) soil liquefaction induced by ground shaking. Major seismic hazards have been observed to come from large ground movement/rupture along fault or soil liquefaction zones. Since seismic shaking affects a large area, the design and construction of buried pipeline under a seismic shaking environment is unavoidable. Therefore all causes of seismic hazards to buried pipelines must be considered.

The responses/failures of buried continuous oil and gas pipelines due to ground rupture and fault movements have been studied by several authors. In consideration of the influence of large fault movement to buried pipelines, all these studies used static analysis with small or large deformation theory. To accommodation the large ground rupture or fault movements, material plasticity (yielding) was employed. The failure under a strike-slip fault would mostly be in tension. Depending on fault crossing angle, failure may be in compression, shear or combination of axial and bending.

Recently, the failure mechanisms of buried pipeline in a soil liquefaction environment induced by seismic shaking have been studied. However, these studies are only preliminary and no design criteria have yet been developed for such conditions. In the absence of soil restraints under liquefaction environment, dynamic analysis would be most proper. The failure of the pipeline would be due to dynamic axial tension or buckling, lateral/vertical bending/vibrations, as well as uplift due to buoyancy.

The effects of wave propagation from seismic ground shaking of buried straight pipelines located within uniform firm soil have been found to result in relatively minor damage. However, pipeline damage from recent Mexico City Earthquake (1985) and Whittier California Earthquake (1987) were from seismic wave propagation effects without ground rupture or soil liquefaction.

For seismic shaking effects, the damaged area is mostly at regions where the soil and/or geological conditions change and at joints and junctions. The failure mechanisms of pipe itself environment without liquefaction are bending and shear fractures, axial tension and buckling. The block-out failures and longitudinal cracks found during Whittier Earthquake indicated dynamic water pressure or water hamper effects to the water pipes.

In general, because of high soil restraints and damping in regions without soil liquefaction, dynamic effects to buried pipelines would be minimum. Quasi-static approach to analyze buried pipelines has been proposed. There is no seismic design code for buried pipelines.

2.13 Rational Design and Rehabilitation of Water Delivery Systems
(Tommy L. Whitlow)

<u>Methodology for Cost-Benefit Analysis</u>. Develop methods for cost-benefit analysis of water system and fire operations to justify capital improvement, including risk analysis. The political arena requires methods for cost-benefit analysis of improvement to systems and operations and

approval of budgets. This would be of considerable benefit to local agencies so they could testify to the benefits of systems improvements based on probabilistic analysis of all factors involved.

Master Plan for Development. Systems should develop master planning which includes measures for the mitigation of earthquake hazards based on identification of weaknesses, and the plan should also set priorities for correcting these weaknesses. Parts of the system that need special attention would include weaknesses in sources of supply, pipelines that have demonstrated continuing maintenance problems, valve arrangements that are inadequate, and soil conditions indicating probable damage from earthquakes.

Improve Maintenance Systems. Maintenance based on systematic record keeping will identify parts of pipeline systems which will suffer more than average damage during earthquakes. Arguments based on economics in favor of maintenance and rehabilitation under normal operating conditions will also provide benefits in earthquake response. The economic basis of these improvements should be emphasized.

Emergency Planning. We need to develop our plans for both regional and local specifics and to have scenarios developed for various events that may occur as both the regional and local agencies will be interrelated. As part of an emergency plan, priorities for water flow demands to various parts of the city would be extremely important to the fire service in trying to conserve the available water to critical areas. As an example, there could be certain regional areas where no fires were reported and the water could be valved off to provide water to more critical areas such as hospitals, nursing homes, schools, homes, etc. We need to develop plans for water restoration to institutions such as hospitals. Hospitals, schools, and nursing homes will be critically important after an earthquake.

Methods to provide redundancy should be developed for the alternate or various possible failures with the system. We need to consider redundancy to provide for duplication of transmission mains and alternate sources of power for pumping stations, communications and control operations.

Another aspect is to have necessary portable equipment, either stored or on hand, to cover some of the emergency plans. It should also include portable chlorinated equipment available so potable water can be on hand. To allow the best use of portable equipment, consideration should be given for providing special hook-ups for important institutional facilities, such as hospitals and schools. This will allow a hook-up for restoration of water on a preferential basis during an emergency so that this resource could be provided to those with critical need.

Valve Arrangement. The need to know the valve arrangement of each water system and to develop operational programs for operation of the valve systems as each specific scenario would dictate. For example, after an earthquake, it may be critical to isolate locations of serious pipeline damage so that pressure and flow could be reserved for other parts of the system and prevent the depletion of reservoir storage. Computer assisted programs to indicate rapidly which valves to operate and maintain the integrity of the system.

Better Definition of Ground Failure Hazards. There is a need to identify and to more adequately describe the potential for large ground deformations and its effect on buried pipelines during an earthquake. Of special importance are areas of potential liquefaction and the pattern of ground deformation that results from this phenomena. Other important types of ground deformation include slope instability, surface faulting, and locations of severe differential settlement.

SECTION 3
POSITION PAPERS

3.1 Methods for Serviceability Analysis of Water Delivery Systems

Group: M. Grigoriu
M. J. O'Rourke
C. R. Scawthorn
M. Shinozuka
C. E. Taylor
C. F. Voyles
L. R. L. Wang

Work to date focused on several topics including

- Development of an interactive-graphical preprocessing and postprocessing computer code, GISALLE, for evaluating the serviceability of water delivery systems (Cornell University);
- Reliability, connectivity, and serviceability research on performance of network systems (Princeton University);
- Studies on global risk assessment of water delivery systems (Rensselaer Polytechnic Institute);
- Demand estimation in relation to fire (EQE, Inc.); and
- Field experiments at Parkfield for estimating seismic performance of pipelines (Weidlinger Associates).

Participants to the workshop evaluated current accomplishments of researchers associated to the National Center of Earthquake Engineering Research and provided suggestions on future work. Their views are summarized in the next sections.

Evaluation of Work to Date

- Current studies by NCEER researchers involve water delivery systems in San Francisco, Los Angeles, and Memphis. This choice is appropriate due to the diverse nature, characteristics, and location of these systems;
- A significant accomplishment of the workshop is that for the first time emergency responders (e.g., fire departments) have been brought and asked to contribute to the lifeline serviceability evaluation;

- Current reliability, serviceability, and connectivity analyses involve a single level within the hierarchy of water delivery systems, i.e., the municipal systems;
- GISALLE and related computer codes represent a major advancement in the performance evaluation of water delivery systems. GISALLE is user friendly, makes feasible the development of "smart" pipeline systems and of rational strategies for emergency planning, and provides an efficient tool for post-earthquake damage analysis;
- Demand evaluation studies have broadened the scope of serviceability analysis by introducing a new component of uncertainty related to the random nature of fires;
- Field experiments at Parkfield are innovative, timely, and have the potential of producing most useful data. Similar creative experiments are encouraged; and
- Work on global risk assessment of water delivery systems provides an excellent overview on expected seismic performance of water delivery systems.

Future Directions

- Continued interaction between emergency responders and lifeline engineers is strongly encouraged;
- Continue development, verification, and transfer (e.g., to PC's) of computer codes for serviceability analysis, especially interactive-graphical preprocessing and postprocessing codes (e.g., GISALLE). Future codes should account for the transient nature of demand;
- Combine probabilistic models for demand and capacity to study effects of uncertainties in demand and capacity on serviceability of water delivery systems;
- Extend serviceability studies and computer codes to other levels of the hierarchy of water delivery systems (e.g., transmission systems, pump stations, storage facilities);
- Refine current methods for estimation of liquefaction potential and incorporate these methods to lifeline analysis;
- Encourage systematic and coordinated post-earthquake data collection;

- Continue analytical studies of seismic performance of components (e.g., pipes, joints, pump stations); and
- Use GISALLE and related codes to perform cost/benefit studies of "smart" systems. If usefulness can be proven, hardwares have to be designed for implementation.

3.2 Rational Design and Rehabilitation of Water Delivery Systems

Group: F. Blackburn
F. Borden
H. Cornell
H. D. Crossnine
T. Dickerman
J. Isenberg
T. D. O'Rourke
T. Whitlow

The group was composed mainly of system operators and those specializing in the practical aspects of buried piping performance and network characteristics. The group focused on the practical problems facing water delivery systems from financial, maintenance, and operational perspectives.

There was general support for the research program in lifelines sponsored by the National Center for Earthquake Engineering Research. It was felt that research should be directed to real systems, and that by showing proof of concept for several case study areas, the research findings would have a strong chance of success when applied to the water supply industry at large.

Research focused on the case study areas of San Francisco, Los Angeles, and Memphis was perceived as covering a good, representative cross-section of different water delivery systems. It was pointed out that San Francisco has a special distinction in operating an independent water supply expressly for fire fighting purposes. The only other U.S. cities operating independent fire supplies are Boston, Philadelphia, and New York City.

The group discussion was concentrated on identifying future research and application directions which would have the most benefit for those managing and operating water delivery systems. Six areas of productive research and application were identified, and summary statements about those areas were drafted and circulated among the group members for additional written comments after the workshop. The six areas are described, based on workshop discussion and written comments, under the headings which follow.

Methodology for Cost-Benefit Analysis. There is a need to develop methods for cost-benefit analysis of potential improvements in water systems and fire operations to justify capital expenditures. Political support for bond issues or capital improvement programs requires a cost-benefit evaluation, with future benefits converted to present worth. Risk analysis should be part of the assessment program.

Master Plan for Development. Utilities should develop master planning for mitigating the effects of earthquakes. The master plan should identify the weaker components of the system and set priorities for correcting the weaknesses. Portions of the system which need to be evaluated are sources of supply (such as intake structures inadequately designed for earthquake loads), pipelines that have demonstrated continuing maintenance problems, valve arrangements that are inadequate, and soil conditions indicating probable damage from earthquakes.

Improved Maintenance Systems. Emphasis should be placed on keeping good, reliable, and complete maintenance records. Parts of the system with heavy maintenance should be targeted for rehabilitation. Improved maintenance not only helps during normal operations, but also provides benefits in earthquake response. The economic basis of these improvements should be emphasized.

In gathering maintenance records, one must take into consideration that a large percentage of water mains are not installed and maintained by the public utilities but by private contractors on private properties. Examples are apartment complexes and large warehouse developments. Maintaining these systems is the responsibility of the private owners.

<u>Emergency Planning</u>. There is a need for emergency planning, with close coordination between both regional and local agencies. As part of an emergency plan, priorities for water flow demands to various parts of the city would be extremely important to the fire service in trying to conserve the available water to critical areas. As an example, there could be certain regional areas where no fires were reported and the water could be valved off to provide water to more critical areas such as hospitals, nursing homes, schools, homes, etc. We need to develop plans for water restoration to institutions such as hospitals. Hospitals, schools, and nursing homes will be critically important after an earthquake.

Economical methods to provide redundancy in flow paths should be developed. Some areas to be examined are transmission mains and alternate sources of power for pumping stations, communications, and control operations.

Another aspect is portable equipment, either stored or on hand, to cover some of the emergency needs. Portable chlorination equipment should be available. To allow the best use of portable equipment, consideration should be given to providing special hook-ups for important institutional facilities such as hospitals and schools. The hook-ups will allow rapid and selective restoration of water to critical service areas during an emergency.

An emergency plan should include all segments of the community, including private industry. For example, fire sprinkler companies can be utilized in time of emergency to assist in the installation of valves for the emergency supply of water to a given location. Irrigation companies can be called to utilize portable piping to route water. Fuel for emergency pumps, generators, etc., can be obtained from a local refinery or fuel storage facility. One must keep in mind that in most communities the prime portable mover of water is the fire department with most pumpers designed to deliver 1500 gpm. Fire departments should have considerable amounts of extra fire hose and proper valving available in time of emergency.

Value Arrangement and Operation. There is a need to know the valve arrangement of each water system and develop an operational program for emergency cut-offs and water diversions. For example, after an earthquake, it may be critical to isolate locations of serious pipeline damage so that the pressure and flow could be reserved for others parts of the system and prevent the depletion of reservoir storage. Computer assisted programs to indicate rapidly which valves to operate and maintain the integrity of the system would be beneficial. The use of serviceability analysis coupled with remotely controlled valves holds great promise as a means of rapidly evaluating the characteristics of a damaged system and reconfiguring the system through remote control of valves to optimize response.

Better Definition of Ground Failure Hazards. There is a need to identify and to describe more adequately the potential for large ground deformation and its effects on buried pipelines during an earthquake. Of special importance are areas of potential liquefaction and the pattern of ground deformation that results from this phenomena. Other important types of ground deformation include slope instability, surface faulting, and locations of severe differential settlement.

APPENDIX A

September 26, 1988

PRELIMINARY PROGRAM

Wednesday, November 30, 1988

Afternoon	Arrival	Best Western University Inn East Hill Plaza Ithaca, New York 14850 (607) 272-6100
7:30	Buffet dinner	

Thursday, December 1, 1988

Morning and afternoon sessions at Hollister Hall, Room 201

8:00 a.m.	Registration and coffee
8:30 a.m.	Welcoming Remarks M. Shinozuka, Princeton University
8:45 a.m.	Directions for the Workshop, Introduction of Participants M. Grigoriu, Cornell University
9:00 a.m.	Technical Presentations on: Methods for Serviceability Analysis (Chairmen: M. Grigoriu and C. Scawthorn)
11:30 a.m.	Discussions
12:00 p.m.	Lunch
1:30 p.m.	Presentation of Cornell program for serviceability analysis of water supply system (M. Khater)
2:00 p.m.	Discussions
2:30 p.m.	Technical Presentations on: Rational Design and Rehabilitation of Networks (Chairmen: T. D. O'Rourke and M. Shinozuka)
5:00 p.m.	Discussions
7:00 p.m.	Dinner

Friday, December 2, 1988

Morning sessions at Hollister Hall

8:00 a.m.	Working Groups 1-2, Development of Presentations of Position Papers
10:00 a.m.	Presentation of Position Papers
10:00 a.m.	Working Group 1 (Methods for Serviceability Analysis of Water Delivery Systems)
11:00 a.m.	Working Group 2 (Methods for Rational Design, Operation, and Rehabilitation of Water Delivery Systems)
12:00 p.m.	Lunch

APPENDIX B

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NATIONAL CENTER FOR EARTHQUAKE ENGINEERING RESEARCH
LIST OF PUBLISHED TECHNICAL REPORTS

The National Center for Earthquake Engineering Research (NCEER) publishes technical reports on a variety of subjects related to earthquake engineering written by authors funded through NCEER. These reports are available from both NCEER's Publications Department and the National Technical Information Service (NTIS). Requests for reports should be directed to the Publications Department, National Center for Earthquake Engineering Research, State University of New York at Buffalo, Red Jacket Quadrangle, Buffalo, New York 14261. Reports can also be requested through NTIS, 5285 Port Royal Road, Springfield, Virginia 22161. NTIS accession numbers are shown in parenthesis, if available.

NCEER-87-0001	"First-Year Program in Research, Education and Technology Transfer," 3/5/87, (PB88-134275/AS).
NCEER-87-0002	"Experimental Evaluation of Instantaneous Optimal Algorithms for Structural Control," by R.C. Lin, T.T. Soong and A.M. Reinhorn, 4/20/87, (PB88-134341/AS).
NCEER-87-0003	"Experimentation Using the Earthquake Simulation Facilities at University at Buffalo," by A.M. Reinhorn and R.L. Ketter, to be published.
NCEER-87-0004	"The System Characteristics and Performance of a Shaking Table," by J.S. Hwang, K.C. Chang and G.C. Lee, 6/1/87, (PB88-134259/AS).
NCEER-87-0005	"A Finite Element Formulation for Nonlinear Viscoplastic Material Using a Q Model," by O. Gyebi and G. Dasgupta, 11/2/87, (PB88-213764/AS).
NCEER-87-0006	"Symbolic Manipulation Program (SMP) - Algebraic Codes for Two and Three Dimensional Finite Element Formulations," by X. Lee and G. Dasgupta, 11/9/87, (PB88-219522/AS).
NCEER-87-0007	"Instantaneous Optimal Control Laws for Tall Buildings Under Seismic Excitations," by J.N. Yang, A. Akbarpour and P. Ghaemmaghami, 6/10/87, (PB88-134333/AS).
NCEER-87-0008	"IDARC: Inelastic Damage Analysis of Reinforced Concrete Frame - Shear-Wall Structures," by Y.J. Park, A.M. Reinhorn and S.K. Kunnath, 7/20/87, (PB88-134325/AS).
NCEER-87-0009	"Liquefaction Potential for New York State: A Preliminary Report on Sites in Manhattan and Buffalo," by M. Budhu, V. Vijayakumar, R.F. Giese and L. Baumgras, 8/31/87, (PB88-163704/AS). This report is available only through NTIS (see address given above).
NCEER-87-0010	"Vertical and Torsional Vibration of Foundations in Inhomogeneous Media," by A.S. Veletsos and K.W. Dotson, 6/1/87, (PB88-134291/AS).
NCEER-87-0011	"Seismic Probabilistic Risk Assessment and Seismic Margins Studies for Nuclear Power Plants," by Howard H.M. Hwang, 6/15/87, (PB88-134267/AS). This report is available only through NTIS (see address given above).
NCEER-87-0012	"Parametric Studies of Frequency Response of Secondary Systems Under Ground-Acceleration Excitations," by Y. Yong and Y.K. Lin, 6/10/87, (PB88-134309/AS).
NCEER-87-0013	"Frequency Response of Secondary Systems Under Seismic Excitation," by J.A. HoLung, J. Cai and Y.K. Lin, 7/31/87, (PB88-134317/AS).
NCEER-87-0014	"Modelling Earthquake Ground Motions in Seismically Active Regions Using Parametric Time Series Methods," by G.W. Ellis and A.S. Cakmak, 8/25/87, (PB88-134283/AS).
NCEER-87-0015	"Detection and Assessment of Seismic Structural Damage," by E. DiPasquale and A.S. Cakmak, 8/25/87, (PB88-163712/AS).
NCEER-87-0016	"Pipeline Experiment at Parkfield, California," by J. Isenberg and E. Richardson, 9/15/87, (PB88-163720/AS).

NCEER-87-0017	"Digital Simulation of Seismic Ground Motion," by M. Shinozuka, G. Deodatis and T. Harada, 8/31/87, (PB88-155197/AS). This report is available only through NTIS (see address given above).
NCEER-87-0018	"Practical Considerations for Structural Control: System Uncertainty, System Time Delay and Truncation of Small Control Forces," J.N. Yang and A. Akbarpour, 8/10/87, (PB88-163738/AS).
NCEER-87-0019	"Modal Analysis of Nonclassically Damped Structural Systems Using Canonical Transformation," by J.N. Yang, S. Sarkani and F.X. Long, 9/27/87, (PB88-187851/AS).
NCEER-87-0020	"A Nonstationary Solution in Random Vibration Theory," by J.R. Red-Horse and P.D. Spanos, 11/3/87, (PB88-163746/AS).
NCEER-87-0021	"Horizontal Impedances for Radially Inhomogeneous Viscoelastic Soil Layers," by A.S. Veletsos and K.W. Dotson, 10/15/87, (PB88-150859/AS).
NCEER-87-0022	"Seismic Damage Assessment of Reinforced Concrete Members," by Y.S. Chung, C. Meyer and M. Shinozuka, 10/9/87, (PB88-150867/AS). This report is available only through NTIS (see address given above).
NCEER-87-0023	"Active Structural Control in Civil Engineering," by T.T. Soong, 11/11/87, (PB88-187778/AS).
NCEER-87-0024	Vertical and Torsional Impedances for Radially Inhomogeneous Viscoelastic Soil Layers," by K.W. Dotson and A.S. Veletsos, 12/87, (PB88-187786/AS).
NCEER-87-0025	"Proceedings from the Symposium on Seismic Hazards, Ground Motions, Soil-Liquefaction and Engineering Practice in Eastern North America," October 20-22, 1987, edited by K.H. Jacob, 12/87, (PB88-188115/AS).
NCEER-87-0026	"Report on the Whittier-Narrows, California, Earthquake of October 1, 1987," by J. Pantelic and A. Reinhorn, 11/87, (PB88-187752/AS). This report is available only through NTIS (see address given above).
NCEER-87-0027	"Design of a Modular Program for Transient Nonlinear Analysis of Large 3-D Building Structures," by S. Srivastav and J.F. Abel, 12/30/87, (PB88-187950/AS).
NCEER-87-0028	"Second-Year Program in Research, Education and Technology Transfer," 3/8/88, (PB88-219480/AS).
NCEER-88-0001	"Workshop on Seismic Computer Analysis and Design of Buildings With Interactive Graphics," by W. McGuire, J.F. Abel and C.H. Conley, 1/18/88, (PB88-187760/AS).
NCEER-88-0002	"Optimal Control of Nonlinear Flexible Structures," by J.N. Yang, F.X. Long and D. Wong, 1/22/88, (PB88-213772/AS).
NCEER-88-0003	"Substructuring Techniques in the Time Domain for Primary-Secondary Structural Systems," by G.D. Manolis and G. Juhn, 2/10/88, (PB88-213780/AS).
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NCEER-88-0013	"A Study of Radiation Damping and Soil-Structure Interaction Effects in the Centrifuge," by K. Weissman, supervised by J.H. Prevost, 5/24/88, (PB89-144703/AS).
NCEER-88-0014	"Parameter Identification and Implementation of a Kinematic Plasticity Model for Frictional Soils," by J.H. Prevost and D.V. Griffiths, to be published.
NCEER-88-0015	"Two- and Three- Dimensional Dynamic Finite Element Analyses of the Long Valley Dam," by D.V. Griffiths and J.H. Prevost, 6/17/88, (PB89-144711/AS).
NCEER-88-0016	"Damage Assessment of Reinforced Concrete Structures in Eastern United States," by A.M. Reinhorn, M.J. Seidel, S.K. Kunnath and Y.J. Park, 6/15/88, (PB89-122220/AS).
NCEER-88-0017	"Dynamic Compliance of Vertically Loaded Strip Foundations in Multilayered Viscoelastic Soils," by S. Ahmad and A.S.M. Israil, 6/17/88, (PB89-102891/AS).
NCEER-88-0018	"An Experimental Study of Seismic Structural Response With Added Viscoelastic Dampers," by R.C. Lin, Z. Liang, T.T. Soong and R.H. Zhang, 6/30/88, (PB89-122212/AS).
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NCEER-88-0025	"Experimental Study of Active Control of MDOF Structures Under Seismic Excitations," by L.L. Chung, R.C. Lin, T.T. Soong and A.M. Reinhorn, 7/10/88, (PB89-122600/AS).
NCEER-88-0026	"Earthquake Simulation Tests of a Low-Rise Metal Structure," by J.S. Hwang, K.C. Chang, G.C. Lee and R.L. Ketter, 8/1/88, (PB89-102917/AS).
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